Electrochemical Power for NASA Missions

NASA has a wide range of missions that require electrochemical power sources. These needs are met with a variety of options that include primary and secondary cells and batteries, fuel cells and regenerative fuel cells. This presentation will cover an overview of NASA missions and requirements for electrochemical power sources and investigate the synergy and diversity that exist between NASA's requirements and those for military tactical power sources. Current development programs at GRC and other NASA centers, aimed at meeting NASA's future requirements will also be discussed.

Electrochemical Power for NASA Missions

Tactical Power Sources Summit
Fueling the Future Force

February 1–2, 2005

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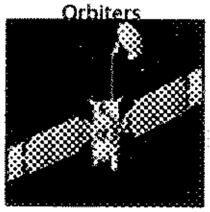
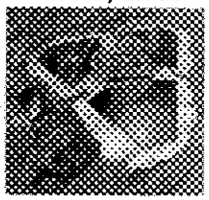
Electrochemical Power for NASA Missions

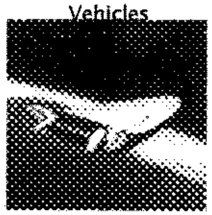
- Overview of NASA Missions
- Requirements for Electrochemical Power Sources
- Current development programs aimed at meeting NASA's future requirements
- Synergy and Diversity Between NASA Military Tactical Power Sources

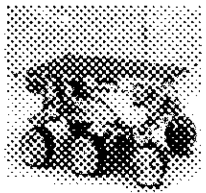
NASA BATTERY APPLICATIONS

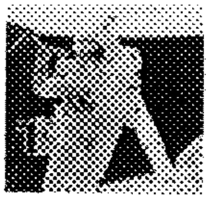
Planetary and Earth Orbiters


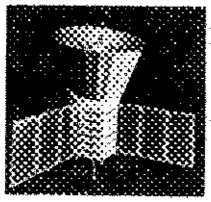
Planetary Lander


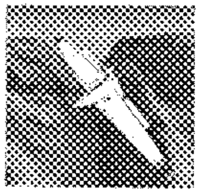
GEO Spacecraft


Reusable Launch Vehicles


Planetary Rover


Astronaut Equipment


LEO Spacecraft


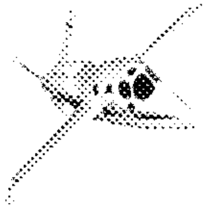
UAV's


NASA CELL AND BATTERY REQUIREMENTS

Parameter	Rovers	Landers	Aircraft	GEO	RLVs	LEO/ Planetary Orbiters
Nominal Voltage	14	28	28-270	28	100	28
BOL/EOL Capacity (AH)	7	20	20	20 -50	200	20-50
Temp Range (°C)	-30 to +45	-20 to +45	-40 to +65	-5 to +30	-40 to + 65	-5 to +30
Life (Cycles)	>500	>500	1,000	1,000	1,000	30,000
Discharge Rate	C/5 to 1C	C/5 to 1C	C	2C/3	C	C
Charge Rate	C/5 to C/2	C/5 to C/2	C	C/20	C	C/2
DOD (%)	50	50	50	75 (max)	50	40

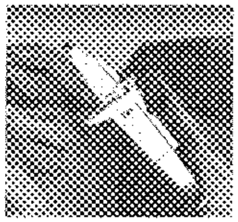
NASA FUEL CELL APPLICATIONS

Small Aircraft

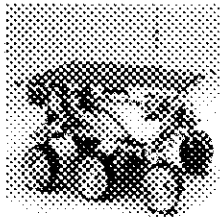


Reusable Launch Vehicles

UAV's

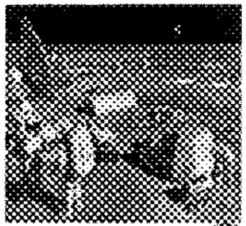


Planetary Rover



Astronaut Equipment

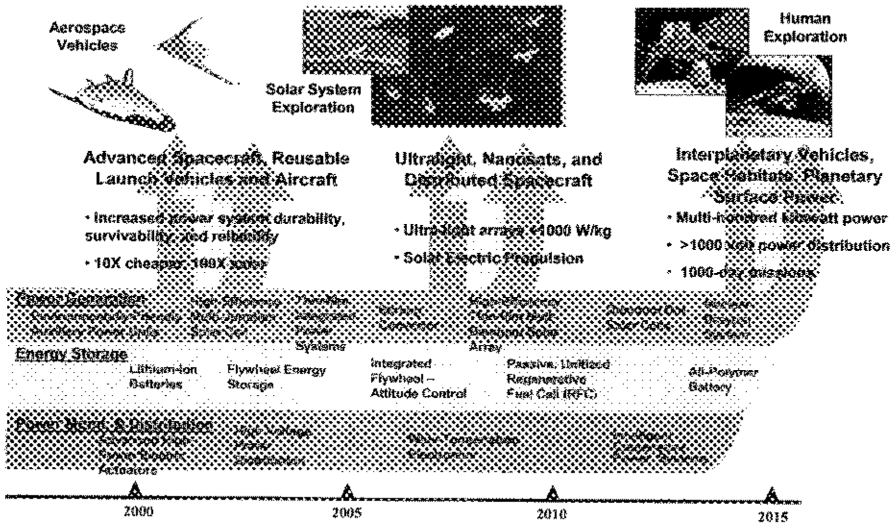
Surface Power



NASA FUEL CELL REQUIREMENTS

Parameter	RLV	Rovers	Surface Power	Aircraft
Nominal Voltage (V)	30	28 - 50	28 - 200	100 - 200
Nominal Power (kW)	2-12	1 - 12	2-10 initial >100 long term	15 - 400
Operating Time	10 days	Hours - Weeks	Days-Years	Hours - Months

Glenn Research Center Aerospace Power Roadmap



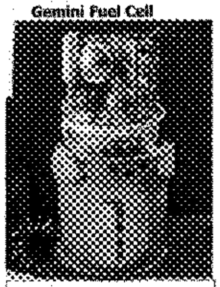
Glenn Research Center Battery Heritage

- Evaluated flight battery technologies for ISS and the Electric Auxiliary Power Unit (EAPU) replacement for the Space Shuttle.
- Developed and validated designs for nickel hydrogen (Ni-H2) cells that have been adopted for NASA missions and employed by cell manufacturers and satellite companies.
- Developed lightweight nickel electrodes, demonstrated the feasibility of bipolar nickel hydrogen battery designs, and developed standard test procedures for evaluating separator materials for alkaline cells.
- A joint DoD and NASA program has successfully developed lithium-ion battery technology implemented the MER rovers.
- Leads the NASA Aerospace Flight Battery System Program, an Agency-wide effort aimed at ensuring the quality, safety, reliability, and performance of flight battery systems for NASA missions.

Glenn Research Center Fuel Cell Heritage

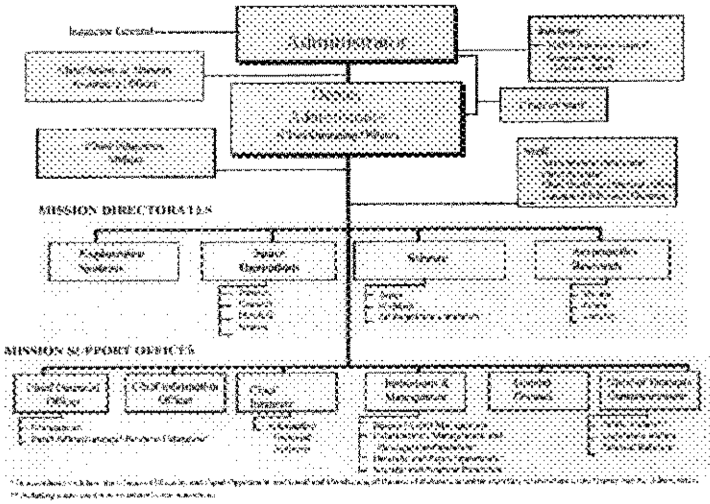
- Conducted technology advancement programs on Gemini Proton Exchange Membrane (PEM) and Apollo alkaline fuel cells.
- Advanced and qualified primary fuel cell power technology for the Space Shuttle onboard power system.
- Developed the technology and supported advanced development activities for the alkaline fuel cells for the Apollo missions and the Space Shuttle.
- Leads development of modular PEM fuel cell stack technology for use in Launch Vehicles.
- Leading the effort to evaluate and develop fuel cell and regenerative fuel cell energy storage systems for missions with long eclipse periods, such as Lunar/Mars bases, UAVs, and high altitude balloons.


Gemini Fuel Cell


Apollo Fuel Cell

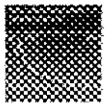

Space Shuttle Fuel Cell Powerplant

NASA Organizational Structure

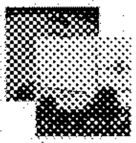


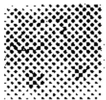
Aeronautics Research Mission Directorate Programs and Objectives

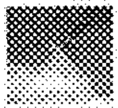
Theme Objectives


Protect Air Travelers and the Public


Protect the Environment


Increase Mobility

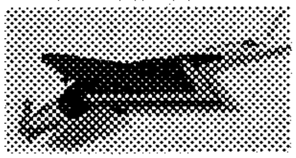

Protect the Nation


Enable New Missions

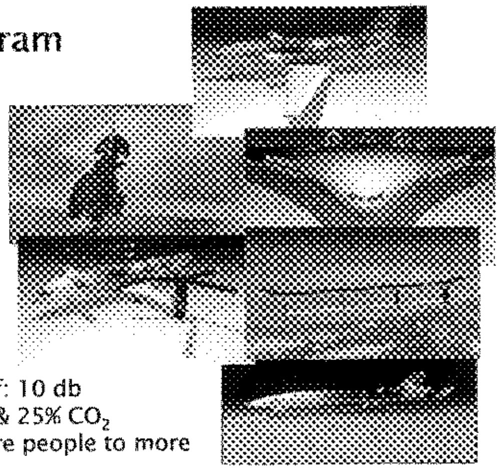
Programs


Airspace Systems


Aviation Safety & Security


Vehicle Systems

Vehicle Systems Program



Goal:

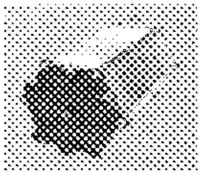
Enable key vehicle capabilities to fulfill the needs of the future air transportation system

Objectives:

- Reduce aviation noise by half: 10 db
- Reduce emissions: 70% NO_x & 25% CO_2
- Increase public mobility: more people to more places in less time
- Enable new aeronautical missions for Earth and planetary science
- Develop partnerships to leverage and enhance National aviation capabilities

VEHICLE SYSTEMS

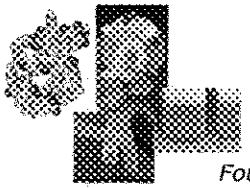
LEAP - Low Emissions Alternative Power



Aircraft Fuel Cell Power Systems

POWERED BY H2

Alternative Propulsion Systems



Alternative Energy Foundation Technologies

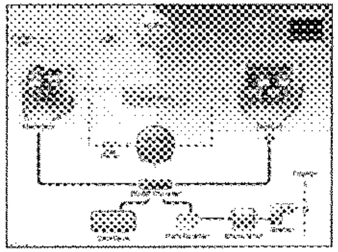
Aircraft Fuel Cell Power System

Two Investment Areas:

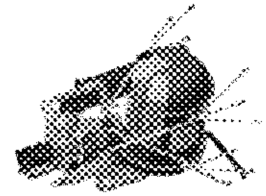
- *Regenerative Fuel Cell to enable high altitude, long endurance flight (Exploration Arial Vehicles).*
- *Consumable Fuel Cell Technology as an alternative aircraft power source for fuel savings, quiet operations, and low emissions.*

FY04 FY05 FY06 FY07 FY08 FY09

- **Initial Aircraft Fuel Cell Benefits Assessment**
- **Adv. Fuel Cell Technology Maturation Plan**
- **Regen PEM Fuel Cell Breadboard Tests**
- **Regen PEM Fuel Cell with 2x SOA Specific Energy Demonstrated in a Relevant Environment**



Regenerative PEM Fuel Cell Energy Storage System



Advanced Fuel Cell Power System such as a Solid Oxide Fuel Cell, Turbine Hybrid for aircraft secondary power

Aircraft Fuel Cell Power System (AFCPS) Subtasks

- Regenerative Fuel Cell Technology (RP, DR)
- Configuration and Performance Evaluation (RT, RI, RP, PB)
- High Temperature PEM Electrolyte Material Development (RM)
- High Performance, Long Life SOFC (RM)
- Compact Lightweight Jet Fuel Processing (RT)
- Power System Critical Component Technology Development (RP)
- Integrated System Development and Demonstration

Regenerative Fuel Cell Development

FY04 FY05 FY06 FY07 FY08 FY09

- **Demonstrate >100 hr repeated diurnal cycles w/o intervention, no degradations**
- **PEM Fuel Cell with Regenerator Demonstration in Relevant Environment (TRL-5)**

Objective:

- *Develop operational regenerative fuel cell (RFC) energy storage system suitable for high altitude unmanned solar electric aircraft*
  - ***>600 W-hr/kg (Target Goal)***
  - ***>50 % round trip efficiency***
  - ***>1000 hr service life***
- *Reduce to practice the operation of RFC as energy storage device.*

Approach:

- *Mature H2-O2 PEM regenerative fuel cell technology developments begun under ERAST to TRL 5-6*
- *Test experimental fuel cell + electrolyzer stacks, proto-flight components in closed loop environment, obtain service data.*
- *Solve developmental problems; gain operating experience*
- *Configure flight ground test unit per experience, test in flight environment*

Technical Challenges:

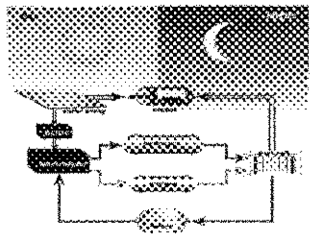
- *Demonstrate power density, efficiency and acceptable life using PEM technology*
- *Reliable ancillary components, instrumentation and controls*
- *Software interface that minimizes human intervention*
- *Fully compliant operational safety practice*

Deliverables:

- *Fuel cell and Electrolyzer stack performance tests*
- *Closed loop regenerative fuel cell performance tests*
- *Test data, technical reports and presentations*
- *Flight prototype design + dev. plan*

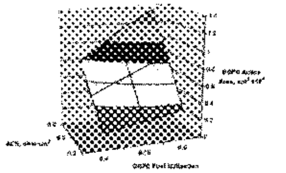
Facilities:

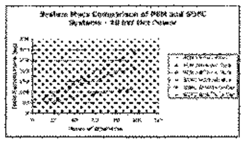
- *Building 135 Closed loop regenerative fuel cell test rig*
- *RCL 24 C H2-O2 PEM fuel cell and electrolyzer test stands*



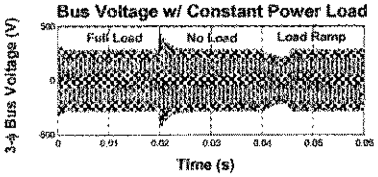
Configuration and Performance Analysis

Performance Analysis

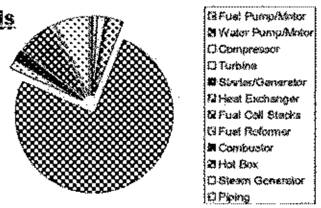




Controls Modeling and Analysis



Weight Analysis



High Temperature Polymer Membranes PEM Fuel Cells

Objective:
Improve the power density and durability of PEM fuel cells

Goal:
Develop new, low cost polymeric membranes that can operate effectively at 120-180°C at zero or low relative humidity (<25%)

Current PEM Membranes
- Expensive: Nafion 117 $750/m^2$, $2500/lbs !
  Dow Membrane $1700/m^2$
- Hydrated membrane: loses its effectiveness above 80 °C due to drying out of the membrane

Benefits:
Increasing the PEM fuel cell operating temperature from 80°C to 120-180°C at zero or low relative humidity
- Increases fuel cell power output
- Reduces susceptibility of catalyst to CO poisoning
- Greatly simplifies the system design (water management, parasitic losses from compressors and humidifiers)

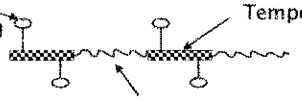
GRC Polymer Membranes

ORMOSil– Organically Modified Silicate

Polymer Designed for Efficient Proton Conduction & Moisture Retention

Proton Conducting Sites

Rigid Portion Provides Strength and High Temperature Stability/Performance

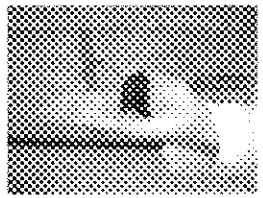


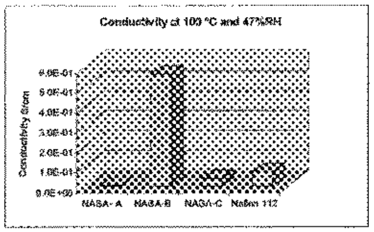
Hydrophilic Portion Binds Water/Ionic Liquids

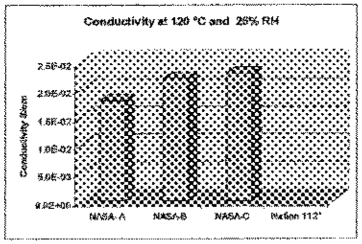
New GRC membrane materials are superior to Nafion:
- ✓ Retain water better at higher temperatures
- ✓ Have proton conductivities at least 100X that of Nafion at high temperatures (120°C) and low relative humidity (25%RH)
- ✓ High proton conductivities at 160 °C at zero RH using ionic liquids
- ✓ Inexpensive – Estimated cost <$100/lbs!

New GRC Developed PEM Membranes Have Good Conductivities at High Temperatures and Low Relative Humidity

New membranes are:
- **Flexible and mechanically robust**
- **Low cost**
- **Have good proton Conductivity at 120 °C and Low Relative Humidity (25%RH)**







* Lower than the detection limit

Ionic Liquids– Zero Humidification Membranes

Strong Acid + Base = Ionic Liquid

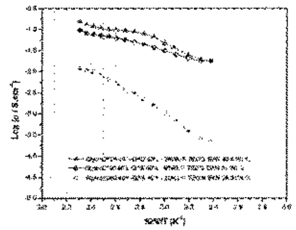
Advantages
- No Humidification required!
  - Greatly simplifies water management in a fuel cell stack
- High Ionic Conductivities ($>10^{-1}$ Scm^{-1})
- Allows operating of the fuel cell at high temperature (>120 °C)

Disadvantages
- Material is a liquid – leaching out of the liquid in an operating fuel cell results in a loss of conductivity and performance

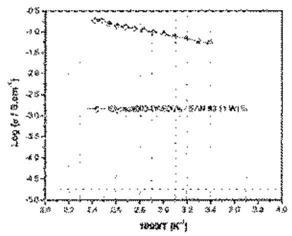
Research Approach
- Incorporate ionic liquids into a specially designed matrix material that is able to both retain the ionic liquid and enhance the catalytic performance of the MEA
- Develop new ionic liquids with good high temperature proton conductivity

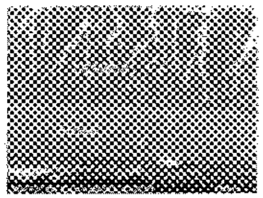
Membranes with Ionic Liquids in NASA ORMOSil Matrix

Ionic liquid ethyl ammonium nitrate (EAN)) added to polymer film

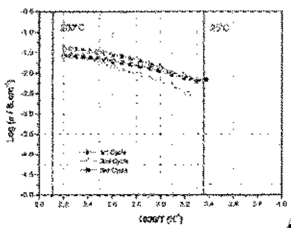


Tetraethoxysilane (TEOS) cross-linked into ORMOSIL polymer at various concentrations. EAN added to the polymer film

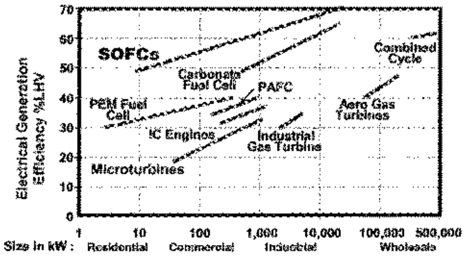




EAN added to cross-linked aerogel coated with the ORMOSil polymer



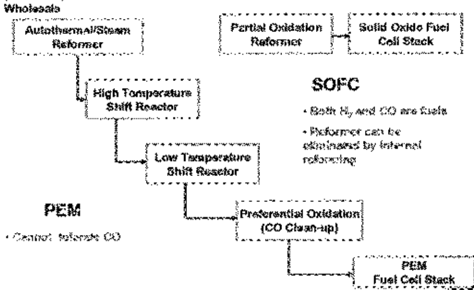
High Performance Long-Life Solid Oxide Fuel Cells



Source: EPRI - Energy Power and Research Institute, Palo Alto, CA

SOFC-based systems offer the highest efficiency, particularly when combined with gas turbine cycles

SOFC-based systems offer a much simpler system for using hydrocarbon fuels



High Performance, Long Life Solid Oxide Fuel Cell

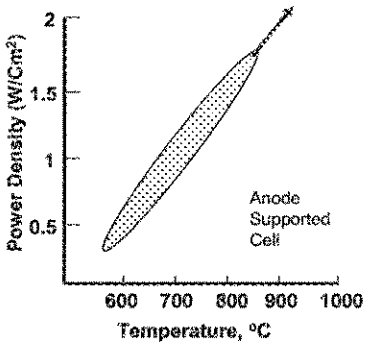
Development of a high power density SOFC system will enable applications that are not possible with current state-of-the art SOFC

Attribute	Current Capability	Aircraft Goal
Total Power	2–5 kW (Planar) - dev > 100 kW +(tubular) > 1 MW (planned)	5 kW for early aircraft application 450 kW for 305 passenger 3 – 10 kW (DOE SECA ground transportation)
Specific Power for Entire SOFC system	0.02–0.04 kW/kg - developmental	0.5 kW/kg (NASA/DOD) 0.1 kW/kg (DOE SECA Program)
Specific Power for Stack	< 0.2 kW/kg for stacks with 1–5 kW total power	1 kW/kg
Power Density for cell/stack (W/cm^2)	1 W/cm^2 cell 0.3 W/cm^2 stack	>1 W/cm^2
Fuel Reformation	Mature at the industrial scale	Compact, lightweight system with high conversion efficiency
Sulfur Tolerance	Limited exp. With logistic fuels, 100's of hrs (ground based)	40,000 hr operating life required for commercial aircraft APUs, & time between maintenance TBD.

SOFC Challenges for Aircraft Applications

- Increasing power density
- Sulfur tolerance
- Durability under aircraft operating conditions
  - Seals
  - Thermal cycling
  - Vibration
- Increasing stack size for higher total power requirement
  - Manufacturing large size cells

Higher Operating Temperature for Increasing Specific Power Density



Higher operating temperatures also desirable for SOFC–gas turbine hybrid systems

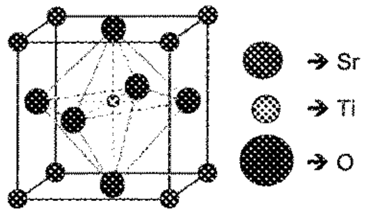
Challenges:
- High temperature ceramic interconnect
  - High electronic conductivity
  - Oxygen permeability
  - Sintering at cell fabrication temperatures
- Seals
- Strength and durability at high temperature

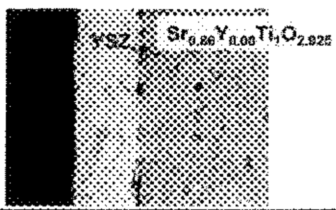
Current Activities:
- Evaluation of electrochemical performance and stability of anode supported cells at higher temperatures
- Various ceramic interconnect concepts
  - Increase conductivity of $LaCrO_3$–based materials
  - Multi–layer and composite interconnect materials
  - Additives to lower sintering temperature
- High temperature glass seal compositions

Sulfur–Tolerant Anode Development

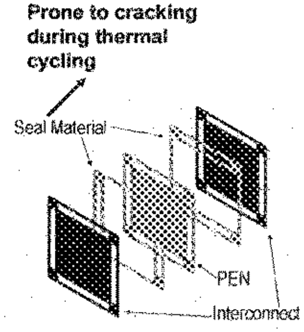
Approach:
- $SrTiO_3$–based material
- Dopants on A–site (Sr)
  - Evaluate effect of ionic radius and electronic orbital configuration
  - Four dopants identified for evaluation
- Dopants on B–site (Ti) – four dopants identified

Progress:
- Processing parameters developed for sintering
- No visible reaction between $SrTiO_3$ and YSZ electrolyte
- Redox stability established





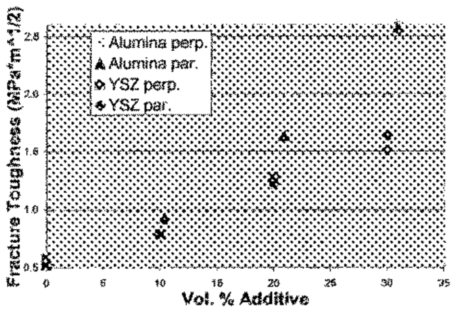
Durability Improvements for Glass Seal Material



PNNL Schematic

Close collaboration with PNNL

Toughness of PNNL glass seal material improved by alumina platelet addition

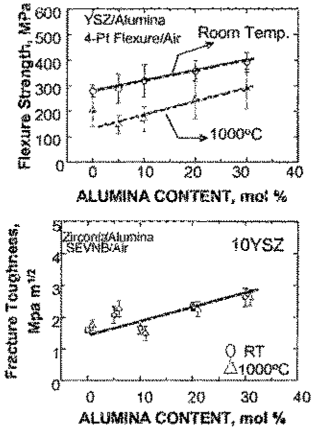


Developing tape cast process for fabricating glass composite seals – other reinforcements, such as BN nanotubes, silicon carbide are being evaluated

Other sealing ideas are being developed Compliant, semi–viscous glass, adv. Seal designs.

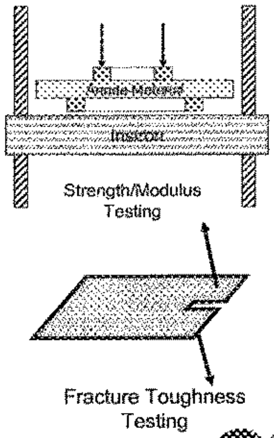
Approaches For Enhancing Cell/Stack Durability

Composite Approach to Enhance Mechanical and Thermal Properties



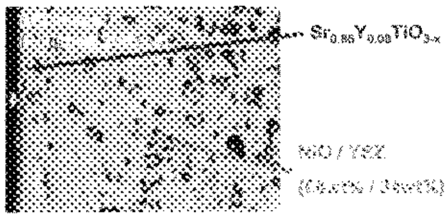
Low Coeff. Of Thermal Expansion (CTE) Anode to Minimize CTE Mismatch

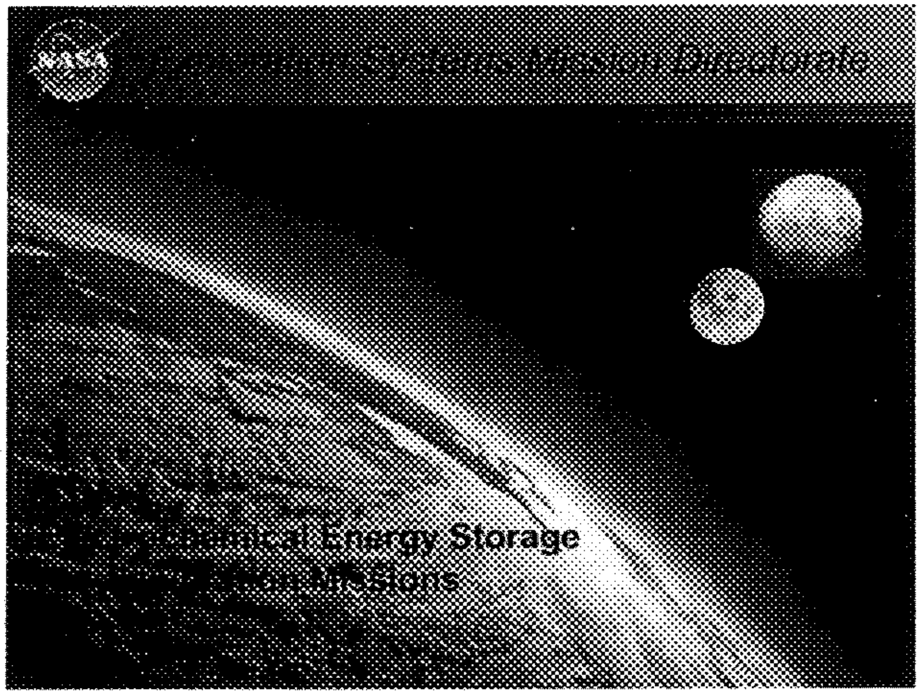
Mechanical Property Measurements



Development of Low Coefficient of Thermal Expansion (CTE) Anode to Improve Durability

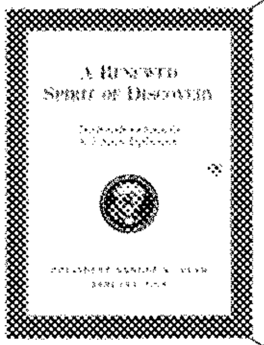
- Expansion mismatch between anode and electrolyte results in thermal stresses during cycling (high expansion due to Ni in Ni+YSZ anode)
- Multiple options being pursued for lowering CTE of anode
  - Blending of low CTE inert or synergistic additives
  - Complete substitution of YSZ for low CTE ionic conductor
  - Novel processing methods to optimize particle interconnectivity and minimize Ni loading





The Vision for Space Exploration

THE FUNDAMENTAL GOAL OF THIS VISION IS TO ADVANCE U.S. SCIENTIFIC, SECURITY, AND ECONOMIC INTEREST THROUGH A ROBUST SPACE EXPLORATION PROGRAM



- Implement a sustained and affordable human and robotic program to explore the solar system and beyond
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations;
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration; and
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests.

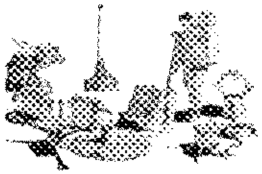
Exploration Systems Mission Directorate
Key Objectives & Milestones

Objectives

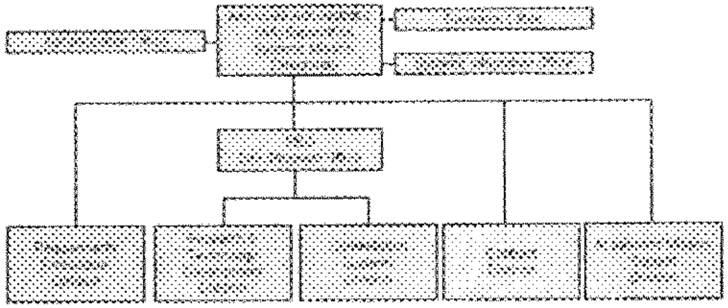
- Implement a sustained and affordable human and robotic program
- Extend human presence across the solar system and beyond
- Develop supporting innovative technologies, knowledge, and infrastructures
- Promote international and commercial participation in exploration

Major Milestones

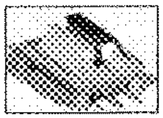
- 2008: Initial flight test of CEV
- 2008: Launch first lunar robotic orbiter
- 2009-2010: Robotic mission to lunar surface
- 2011: First uncrewed CEV flight
- 2014: First crewed CEV flight
- 2012-2015: Jupiter Icy Moons Orbiter (JIMO)/Prometheus
- 2015-2020: First human mission to the Moon

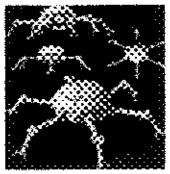


Exploration Systems Mission Directorate



Exploration Systems Research & Technology (ESR&T) Overview





ESR&T is a strategic, requirements-driven investment that enables future exploration systems and missions that are more affordable, reliable, effective and flexible.

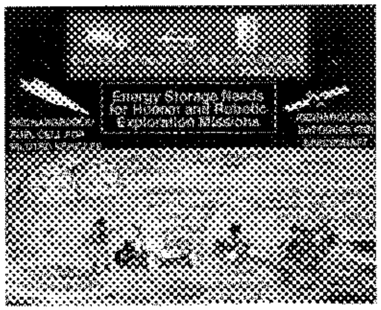
- **Investments range from...**
  - Lower technology readiness level (TRL) R&D projects for the mid- to far- term through the **Advanced Space Technology Program**, to...
  - Higher TRL projects for the near- to mid- term through the **Technology Maturation Program**, to...
  - Cross-cutting efforts to engage universities, small business and the entrepreneurial community through the **Innovative Partnerships Program**, and...
  - Novel approaches to engage private sector innovation and investment through the **Centennial Challenges** 'prizes' program
- **Projects support future ESMD 'system development spirals'**
  - Delivering timely data to inform systems decisions based on R&D
  - High-leverage new technologies incorporated into future systems

Advanced Electrochemical Energy Storage Devices for Human and Robotic Missions

ICP Awarded to JPL - Participation from GRC, JSC, MSFC

ASTP Development

Kickoff - January 2005



Phase-I - One-year effort

Define device requirements

Formulate Phase-II implementation plan

Demonstrate technical feasibility of the devices with laboratory cells.

Phase-II - Three-year effort

- Develop engineering model (EM) rechargeable and primary batteries and fuel cell systems,
- Demonstrate enhanced performance capabilities
  - high specific energies
  - improved low-temperature performance
  - enhanced power densities.

Advanced Electrochemical Energy Storage Devices for Human and Robotic Missions

Secondary Battery Technology Development

Objectives

Develop advanced Secondary Li-ion Batteries with:

- Long life (> 10 years)
- High specific energy and energy density (160 Wh/kg and 320 Wh/l)
- Wide operating temperature range (-60°C to +60°C)

Demonstrate suitability for Exploration applications such as astronaut suits, rovers, and human outposts and habitats.

Approach

- Develop 250 mAh/g cathode based on layered manganese oxides with metal dopants, mixed metal oxide materials with surface coatings, lithiated metal phosphates
- Advanced electrolytes – mixed aliphatic carbonates and ester solvents
- Electrolyte Additives – SEI formation
- Non-flammable electrolytes
- Advanced gel polymer electrolytes
- Shutdown separators
- Cell level demonstrations
- Battery level demonstrations

Advanced Electrochemical Energy Storage Devices for Human and Robotic Missions

Fuel Cell Technology Development

Objectives

Develop advanced Polymer Electrolyte Membrane (PEM) H2-O2 fuel cells with:

- Long life (> 10 years)
- High specific power (200 W/kg)
- High efficiency (> 60%)
- Power capability – 100 W

Demonstrate suitability for Exploration applications such as astronaut suits, rovers, and human outposts and habitats.

Approach

- Materials Development – Membranes, MEA, hydrogen storage materials
- Cell/stack development
- Lightweight composite materials, advanced electro catalysts
- System Development
- Miniaturization
- Industry collaboration

Advanced Electrochemical Energy Storage Devices for Human and Robotic Missions

Primary Battery Technology Development

Objectives

Develop Primary Batteries (LiCFx) with:

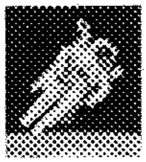
- Long life (> 10 years)
- High specific energy and energy density (400 Wh/kg and 800 Wh/l)
- Wide operating temperature range (-60°C to +60°C)

Demonstrate suitability for Exploration applications such as astronaut suits, rovers, and human outposts/habitats.

Approach

- Materials development – high rate carbon fluoride cathode materials (low temperature fluorination)
- Advanced low-temperature electrolytes – mixed aliphatic carbonates and ester solvents
- Shutdown separators
- Cell level demonstrations
- Battery level demonstrations
- Industrial partners

Human Systems Research & Technology (HSRT)



HSRT is a requirements-driven program focused on reducing long-duration mission cost and risk in the areas of Crew Health & Performance and Life Support & Habitation including EVA.

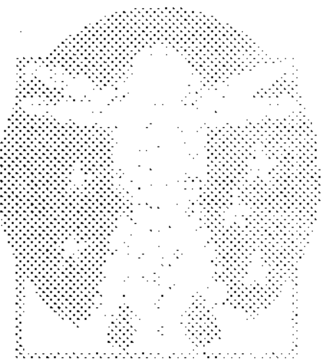
Background

- **Transformed Research Programs from Discipline-based (OBPR) to Requirements- and Product-based (HSRT) Portfolio:**
- **Human Health and Performance** (Radiation Health, Human Health Countermeasures, Behavioral Health & Performance, Autonomous Med Care)
- **Life Support and Habitation** (Advanced Life Support, EVA Technologies, Space Human Factors Engineering, Advanced Environment Monitoring & Control)

Activities

- **Conduct base review of all current programs' technical content**
- **Enlist external research community to support new programs**
- **Align Research & Technology milestones to ISS utilization window**

Advanced Extravehicular Activity to Support the Vision for Space Exploration



A new EVA suit/system will be required to support this new initiative

- The current EVA suit is over 25 years old and is facing significant obsolescence issues
- The current EVA suit is not compatible with the planetary environments of either the Moon or Mars and does not support the logistical requirements of long term missions
- GRC's role is to provide the power subsystem for the EVA suit power system

Advanced Extravehicular Activity to Support the Vision for Space Exploration

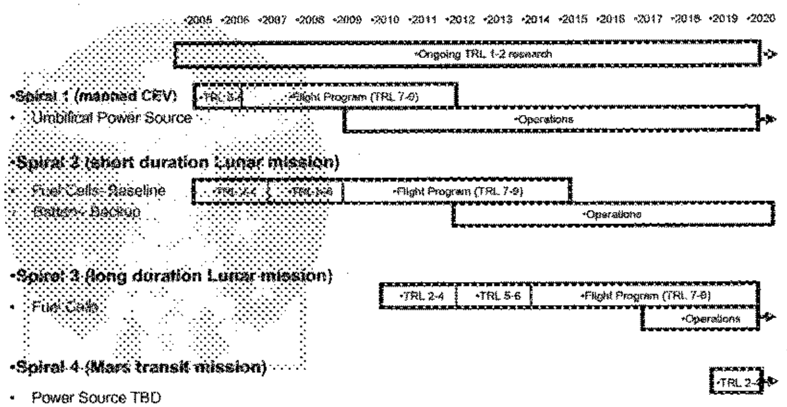
The EVA suit will provide:

- Advanced Life Support (air revitalization)
- Advanced Thermal Control (active heating/cooling)
- Advanced Communications/Computing Capability
- Compatible with in-situ resources available

Providing these capabilities requires a power source that:

- Has high power and energy density (W/kg, W/l, Whr/kg, Whr/l)
- Has long life
- Can be quickly refilled or recharged using available in-situ resources

Advanced Extravehicular Activity to Support the Vision for Space Exploration



PEMFC Power Plant Development for CEV

- Objectives
  - Demonstrate improved capability over existing Shuttle alkaline fuel cell power plant in near-term
    - Enhanced safety
    - Lower weight
    - Longer life
    - Higher peak-to-nominal power capability
    - Reduced hazardous materials and critical failure modes
    - Improved reliability and maintainability
    - Compatibility with propulsion-grade reactants
    - Potential for significantly lower hardware cost
    - Significantly reduced ground processing (major Shuttle recurring cost)

PEMFC Power Plant Development for CEV

- Objectives
  - Replace obsolete Shuttle alkaline fuel cell power plant for far-term
    - In 2010–2015, asbestos raw material for separators will no longer be available
    - Some alkaline power plant components are also becoming obsolete; 30-year old technology
  - Leverage evolving and highly competitive PEMFC commercial market (automotive, residential)
    - Modify commercial designs for space environment to guarantee competition through multiple vendors
      - Pure O_2 operation (vs. air)
      - Zero-g product water separation and removal (vs. gravity-dependent)
    - Take advantage of cost reductions as commercial markets expand and mass-production increases

PEMFC Power Plant Development for CEV

- Description
  - Power plant design is based on modular components and ease of accessibility
    - 6:1 peak power capability within voltage regulation (± 10%)
    - Surge power response times < 1 ms
  - Power plant can be optimized to minimize weight or reactant consumption; configured for multiple voltages
- Background
  - 6-year GRC-led effort to develop PEMFC power plant technology started in FY01
  - NASA team comprises three centers – GRC, JSC, KSC
  - Phase I of program developed Breadboard units using off-the-shelf hardware
    - Advanced from Technology-Readiness-Level (TRL) 4 to TRL 5
    - ElectroChem, Inc. & Teledyne Energy Systems, Inc.
  - Independent NASA testing verified superiority of one vendor and allowed technology down-select

PEMFC Power Plant Development for CEV

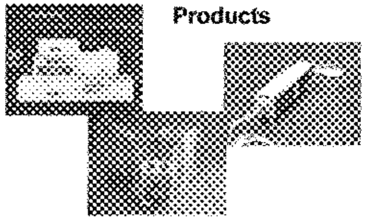
- Status
  - Phase II – Teledyne Energy Systems, Inc. w/ Hamilton Sundstrand (water separators) selected to develop Engineering Model unit – fuel cell stack and all ancillary component hardware (including gravity-independent water separators) – Advance from TRL 5 to TRL 6
- Future Plans
  - Deliver Engineering Model power plant to NASA June 2005
  - Initiate independent NASA testing July 2005
    - Performance testing at GRC
    - Environmental testing (thermal vacuum, vibration) at JSC
  - Perform power plant technology optimization as warranted (optional task)
    - Ejectors vs. pumps for reactant optimization
    - Active vs. passive water separators
    - MEA enhancements
    - Other more advanced concepts (totally passive operation)
  - Continue Membrane-Electrode-Assembly (MEA) endurance testing
    - Achieve 10,000 hours (December, 2005)

Energetics Program

- During FY04 – Energetics – NASA's technology development investment program transitioned into the Exploration Mission Directorate
- FY05 Transition year – Completion of Legacy Technology Development Tasks
  - Advanced Battery Development
  - PERS – Terminated after FY04, transitioned into Advanced Battery Development
  - NASA Aerospace Flight Battery System Program

Energetics: Advanced Energy Systems
Advanced Battery Technology

Products



Product Objectives

- R&D that will lead to advanced Li-based battery systems with >4X specific energy & energy density of SOA nickel based battery systems – capable of operation over a wide range of operating temperatures
  - Advanced Li-ion liquid cell technology
  - Polymer Electrolyte Batteries

Participants

- Li-Ion Liquid Electrolyte Development
  - Advanced component development
    In-house, Carnegie Melon, University of Akron
- Polymer Electrolyte Development
  - In-house, LBL

Customers

- Exploration Systems, Sciences, Space Operations, Aeronautics, Commercial Satellites

FY05 Technical Tasks
Solid-Electrolyte Interphase Studies Determine stability of SEI for polymer electrolytes, address limitations to Li transfer
Safety Assessment Quantify safety aspects of polymer electrolytes
Electrolyte Development Evaluate single ion conductors in cell configurations Evaluate lithium ion transfer with ionic liquid based electrolytes

Advanced Battery Technology

AF NASA Li-ion Development Program Completed in FY04 – Major Accomplishments

- Transitioned lithium ion technology to NASA missions (Lander, Rover) and Air Force mission such as the B-2 (batteries are now in production), Joint Strike Fighter, Global Hawk
- Established Yardney as a viable source of Li-Ion batteries
  - Domestic, US owned source of lithium ion batteries, although many starting materials are obtained from off-shore sources.
  - NASA/AF program credited with building capability that enabled Lithion's success in winning a major lithium ion battery program to support the Navy on an under water vehicle program.
- Demonstrated battery performance down to below minus 40 degrees using electrolytes developed by JPL.
- Demonstrated over 27,000 25% LEO cycles demonstrated (Chuck Lurie of Northrop Grumman)
- Scaleable cell sizes up 200 ampere-hours.
- High power capability. 70 C rate continuous discharges and over 110 C for short pulses to demonstrate ~12kW/kg.

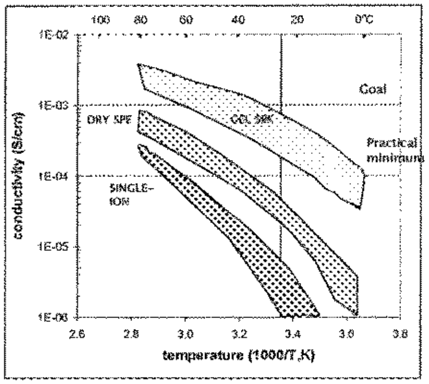
Polymer Energy Rechargeable Systems (PERS)

- Five year effort focused on the development of ultra-safe, conformable advanced polymer electrolyte battery systems with >3X specific energy & 10X energy density of SOA nickel based battery systems
- Combination of in-house, contract and grant efforts aimed at the development of polymer electrolytes with a room temperature conductivity of 10^{-3} S/cm
- FY04 final year of funding – transition into Advanced Battery Development in FY05

PERS Electrolyte Advancements

Goal: 10^{-3} S/cm at room temperature

Material class	S/cm at 25°C
gel SPE	7×10^{-4}
dry SPE	3×10^{-5}
single-ion conductor	$\sim 5 \times 10^{-6}$



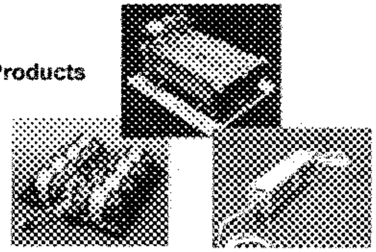
- Gels approach goal – sealing issues?
- Dry SPE approaches practical conductivity above 40°C
- Single-ion conductors eliminate concentration effects but have low conductivity

PERS Baseline Selections

- Lithium metal and vanadium oxide (V_6O_{13}) – baseline electrodes
  - Stability of SPE's restricts cathode to materials with potentials that are <4V vs. Li/Li+.
  - V_6O_{13} has the greatest theoretical energy density: ~900Wh per kilogram of vanadium oxide.
    - Powder of suitable particle size has recently become commercially available.
    - Because V_6O_{13} does not contain lithium, full cells require a negative electrode which provides the lithium cation.
  - Li metal represents the simplest choice for a negative electrode and represents the choice of greatest energy density.
- SPE Candidates selected
  - Most promising SPE's – rod-coil and organically-modified silicate materials.
  - LBL polyelectrolyte leading candidate.
  - Unmodified PEO is being used as a control material in this development

Energetics: Advanced Energy Systems
NASA Aerospace Flight Battery Program

Products



Product Objectives

- Develop, maintain and provide tools for the validation of aerospace battery technologies
- Accelerate the readiness of technology advances and provide infusion paths for emerging technologies
- Provide NASA projects with the database and guidelines for technology selection
- Disseminate validation and assessment tools, quality assurance and availability information to the NASA and aerospace battery communities

Participants

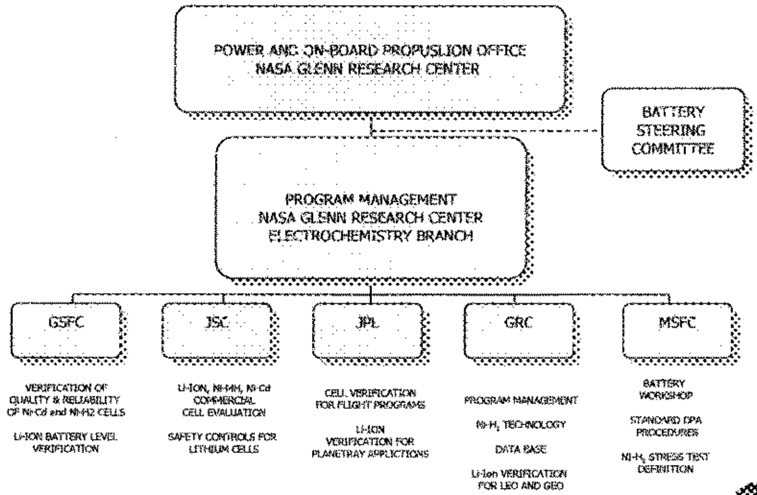
- GRC – Lead – NASA wide program
- GSFC, JSL, JPL, MSFC – participants
- Cell Purchases – Yardney Technical Products, Eagle Picher, Saft, Samsung, Moli, Electrofuel, WGL, Panasonic, Sanyo, AEA Technologies
- Testing Organizations – Navy-Crane, SRI, JPL, Schlumberger, Lockheed Martin
- Handbooks/ Workshops – Aerospace Corp/TBD

Customers

- All NASA missions using battery technology – Sciences, Exploration Systems, Space Operations, Aeronautics, Commercial Satellites, other government programs

FY 05 Technical Tasks
NASA Battery Workshop
Li-Ion Technology Validation – perform testing to validate Li-Ion technology for Exploration mission applications Li-Ion LEO Validation Program
Develop guidelines documents and handbooks – Expert systems failure analysis tool Silver-Zinc Guidelines Document

NASA Aerospace Flight Battery Systems Program Organization

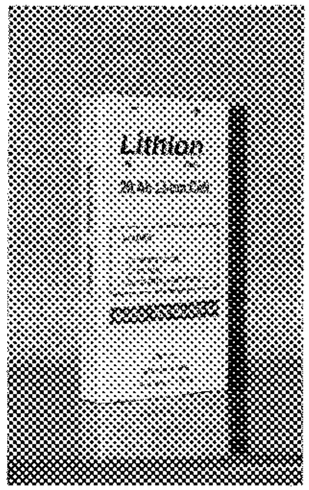


NASA Aerospace Flight Battery Systems Program Accomplishments

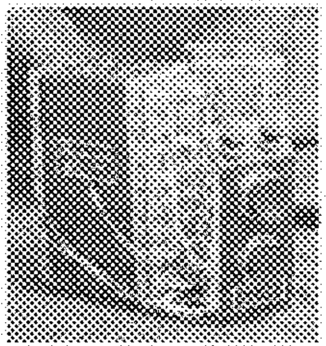
Li-Ion Validation

Established mission readiness of Li Ion batteries for Mars missions

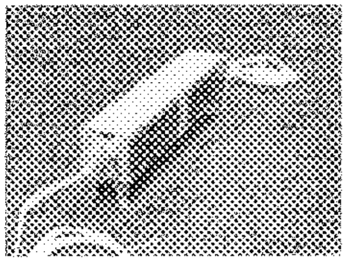
- Demonstrated excellent life at 100% DOD -- prototype versions of Rover and Lander cells
- >60% Capacity retained after 2000 cycles
- Fade rate increases with higher temperatures and decreases with lower temperatures
- Demonstrated >2000 cycles at low temperature –20ºC
- Demonstrated appropriate real-time storage characteristics for prototype Li-Ion cells for long duration missions



Li-Ion Battery Selected MARS 2001 Lander and Mars Exploration Rovers



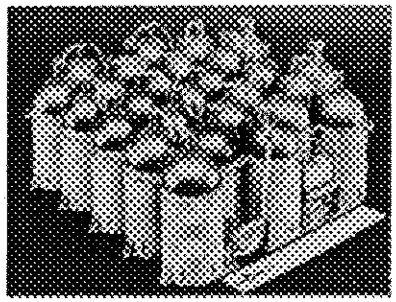
Performance and validation testing of Li-Ion Technology performed by the NASA Aerospace Flight Battery Systems Program provided data base that enabled selection of this new technology for Mars 2001 Lander and Mars Exploration Rover Missions



NASA Aerospace Flight Battery Systems Program

Nickel-Hydrogen Validation

- Generated extensive database for the validation of advanced cell design features for Nickel-Hydrogen
  - Demonstrated improved performance in cells incorporating NASA technology advancements
  - Design features adopted by industry
- Generated data base that demonstrated effects of wet/dry storage
  - Provides missions with an assessment of performance impact related to launch delays
- Demonstrated performance limitations for CPV (Common Pressure Vessel) cells
  - <20000 cycles for current design CPV cells vs >40000 cycles for IPV cells
  - Provides valuable technology selection criteria to match cell design with mission life requirements



NASA Aerospace Flight Battery Systems Program

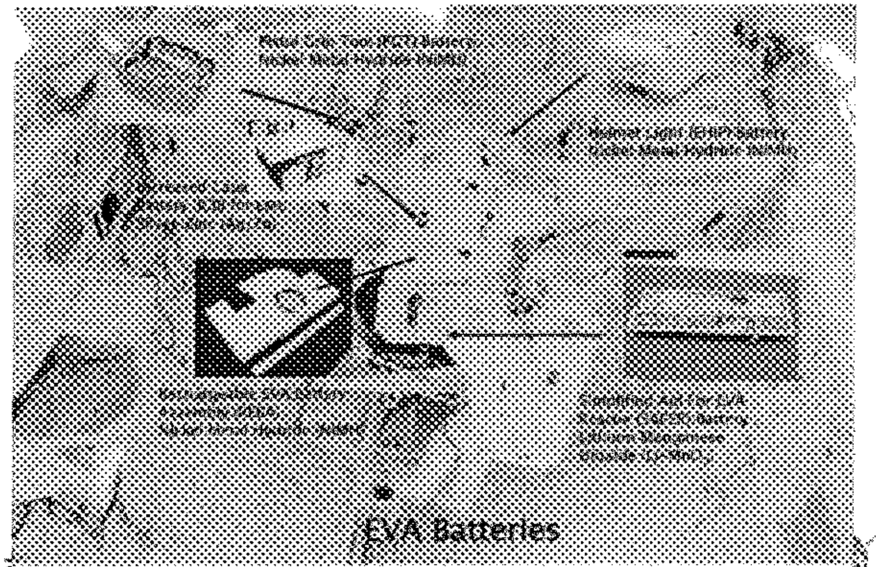
Nickel-Cadmium Validation

- Generated extensive database for the validation of Nickel-Cadmium cell technology - used to qualify alternates to NASA standard cells
- Completed study on Super™ Ni-Cd storage
  - Determined Super™ Ni-Cd cells do not require active storage techniques - simplifies prelaunch operations
- Demonstrated radiation tolerance of Super™ Ni-Cd cells for deep space applications

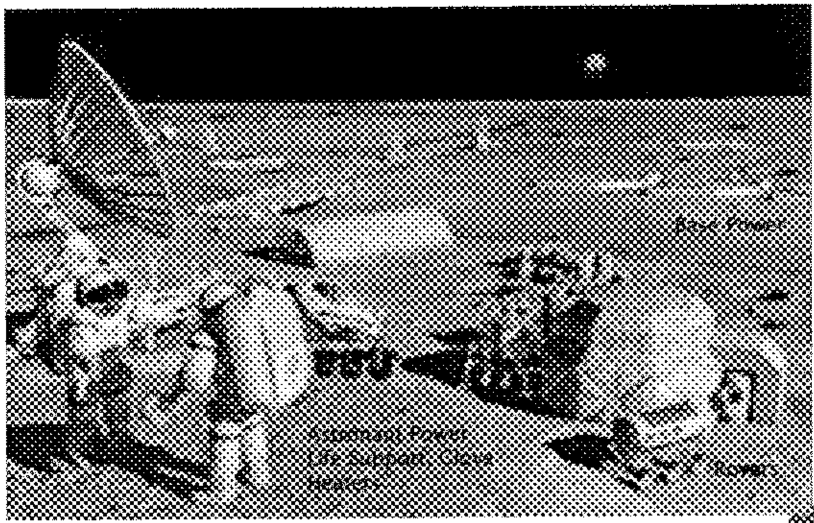
LiBCx Primary Battery Validation

- Developed flight approved version of LiBCX cell that eliminates the need for a waiver for flight approval - earlier versions of the cell were not two fault tolerant
- Expanded its operational limits:
  - Temperature from -40 to +72°C to -65 to 99°C
  - Vibration capability to 30.7 grms max and 1.2 g2/hz max.

Current EVA Power Systems



Surface Power Systems



Synergy with Tactical Power Sources

Tactical Operations Centers	Surface Power Base Requirements
Portable power Disposables are costly No portable recharge capability Too Many battery Types	Astronaut Power Rechargeables are required Controlled recharge capability Commonality -minimize battery types
Base power - logistic fuels	Base power - In situ resource utilization
Soldier Power Minimize battery weight and volume Fast recharge Expanding power demands - more power, less weight Safety	Astronaut Power Minimize battery weight and volume Fast recharge Expanding power demands - more power, less weight Safety

Electrochemical Technology Development Synergy with Tactical Power Sources

Li-Ion
- Improved safety - nonflammable electrolytes
- Wide operating temperature range - performance at extremes
- High specific energy, high energy density
  - High energy cathode materials

Fuel Cells
- Catalyst development
- CO tolerance
- Utilization of logistic fuels
  - Desulfurization
  - Fuel reformation

Concluding Remarks

- Brief Overview of Electrochemistry Development Programs/Research Areas for NASA focused at the Glenn Research Center
- Technical programs directed at meeting NASA's unique needs for reliable, lightweight, compact energy sources
- In many cases NASA needs and developments parallel those for Military Tactical Power Sources
- Future cooperation and coordination of efforts will have mutual benefits